LS-55-Revised
March 1987

SHIELDING ESTIMATES FOR THE ANL 6.0 GeV SYNCHROTRON LIGHT SOURCE

H. J. Moe
V. R. Veluri

1.0 Introduction

Shielding estimates for the linac, positron converter, booster synchrotron and the positron storage ring have been computed using preliminary design information. Calculations have been made of the resulting radiation for several types of operations involving normal beam loss, as well as, certain accidental beam losses. When available, experimental data from existing accelerator and light source facilities have been used in lieu of theoretical estimates.

2.0 Shielding Design Objective

The Department of Energy's basic occupational exposure limit is 5 rem per year (DOE 81). However, in its guidance for maintaining exposures "as low as reasonably achievable" (ALARA), found in the same document, the design objective for new facilities is to limit exposures to one-fifth of 5 rem per year (~ 20 mrem per week). Also, the predicted exposures to the individual members of the public should not exceed 25 mrem per year, the ALARA guide proposed by DOE (DOE 84). These objectives have been used as the basis for shielding design estimates for the normal operations of the facility.

3.0 Types of Radiation Considered

Depending upon the electron energy and beam characteristics, a number of radiation products need to be considered. High energy electrons produce electron-photon cascades or showers when deliberately or accidentally stopped in materials. This component of radiation is referred to as bremsstrahlung radiation and can lead to photon radiation fields outside the shield. The radiation produced in the shower is highly peaked in the forward direction of the electron beam. However, the transverse component is significant and cannot be neglected. As the energy of the electron beam increases, three other components may become increasingly important. The first of these components is the "Giant Resonance" neutrons (GRN) produced by photonuclear interactions. This component has an average effective energy of about 2 MeV and is emitted almost isotropically. When the electron beam energy is in the GeV range, high energy neutrons (> 150 MeV) and muons are also produced. At the maximum electron energy of 6.6 GeV, and the proposed current of 0.3 A, the muons are of minimal importance, since they are highly peaked in the forward direction and their production rate is small. The high energy neutron component (HEN) is not isotropic, but in many shielding situations only the neutron radiation in the transverse direction is of importance. All these radiations have been considered under appropriate conditions in the estimation of shielding requirements. In addition to the above radiations which arise when electrons collide with other materials, photon radiation, called synchrotron radiation, is also produced when e^+ and e^- traverse magnetic fields. For our design, this radiation is generally in the keV region and does not require additional shielding other than the vacuum chamber itself.

4.0 Shielding for Linac and Positron Converter

4.1 Linac Parameters

The relevant physical parameters for the electron linear accelerators and positron converter are as follows:

E = 200 MeVe^- for positron conversion or 650 MeVe^-,

I = 2.5 A at 22 ns pulse width,

f = frequency: 10 Hz,

Electron to positron conversion efficiency in Tungsten: 300:1,

Positron energy: 450 MeV,

Positron current: 8 mA,

Total linac length: 75 m

Tunnel dimensions: 8' × 8'

Beam height: 5' above floor level

4.2 Estimated Beam Losses in the Linear Accelerator System

Since the beam characteristics of the proposed ANL system are similar to the proposed CERN-LEP linac system, estimates of fractional beam losses in the various components of the system were obtained from FASSO, et al (FAS 1984).

Assumed Losses for Positron Production

	I(μA)	LOSS (%)	AVG. ENERGY (MeV)	AVG. POWER (WATTS) e^+	e^-
Gun output	1.36				
		55	5		3.75
Buncher output	0.61				
		10	100		6.0
First Linac output	0.55				
		~100	200		110.0
Second Linac output	1.8×10^{-3}				
		40	225	0.16	
Resolved output	1.1×10^{-3}				

Assumed Losses for Electron Accelerator

	I(μA)	LOSS (%)	AVG. ENERGY (MEV)	AVG. POWER (WATTS) e^+	AVG. POWER (WATTS) e^-
Gun output	1.36				
		55	5		3.75
Buncher output	0.61				
		10	100		6.0
First Linac output	0.55				
		10	425		23.3
Second Linac output	0.50				

4.3 Radiation Attenuation Parameters

Information on the attenuation of the high energy component, giant resonance neutrons and bremsstrahlung radiation by various shielding materials can be obtained from the literature. One encounters a spread in values in the quoted experimental attenuation lengths for a given type of radiation by a given material. A variety of references which discuss these attenuation lengths have been reviewed, such as, BAT 67, ALS 73, TES 79, DIN 77, NEL 68, BAT 70, SWA 79, FAS 84, ETC.

In all cases, we have attempted to use conservative values for these attenuation lengths to provide a margin of safety. The following table gives a listing of the attenuation lengths used for various potential shielding materials.

Radiation Component	Material	Attenuation Length (g/cm^2)
bremsstrahlung	Lead	25
	Concrete	49
	Iron	37
	Sand	70
Giant Resonance Neutrons	Concrete	40
	Dense Polyethylene	6.3
High Energy Neutrons	Concrete	65 (E_n < 100 MeV) 115 (E_n > 100 MeV)

4.4 Radiation Dose Equivalent Factors

The unshielded radiation dose equivalent factors used in the shielding computations have been adapted mainly from FASSO, et al. (FAS 84) with their suggested modifications. These factors are:

Radiation Component	Radiation Dose Equivalent Factor $F_H = \left(\frac{\text{mrem} \cdot \text{m}^2}{\text{J}}\right)$
Bremsstrahlung	2.8
Giant Resonance Neutrons	0.63
High Energy Neutrons	0.075

These factors refer to unshielded dos rates at 1.0 m in the transverse direction to the electron beam. In the forward direction (0 degrees), the value for bremsstrahlung is given by $8.3\ E_o \frac{\text{mrem} \cdot \text{m}^2}{\text{J}}$ (FAS 84, SWA 79) where E_o is in MeV. In general the same values given in the table are used for giant resonance neutrons and the high energy component in the forward direction. It should be noted that in the absence of any shielding, the bremsstrahlung will include a soft radiation component which has been neglected, since the quoted formulas assume shielding will be present.

4.5 Bulk Shielding Calculations

The following formulas were used to compute the bulk shielding requirements for the various components of the light source system:

$$H = \sum_i \frac{F_{Hi}}{r^2} W \quad e^{-d/\lambda_i}, \quad \text{in which}$$

H is the dose equivalent rate in $\frac{\text{mrem}}{\text{s}}$ or $\frac{\text{mrem}}{\text{h}}$,

F_{H_i} is the appropriate factor from the table for the i^{th} radiation component,

r is the source to the dose point distance in meters,

d is the shield thickness in $\frac{\text{g}}{\text{cm}^2}$,

λ_i is the attenuation length for the i^{th} radiation component in $\frac{\text{g}}{\text{cm}^2}$,

W is the energy loss rate in $\frac{\text{J}}{\text{s}}$ or $\frac{\text{J}}{\text{h}}$.

4.5.1 Shielding for the Linear Accelerator System

4.5.1.1 First Linac

The computations for the necessary shielding were based upon the estimated power losses addressed in Section 4.2. The required shielding in any section of the linac is determined by the highest value of power lost. For the first linac, the power loss is greatest between the buncher output and the first linac output (6W). The various computed dose rates for a concrete shielding of 2 m and a total distance of 2.9 m are:

H_{BREM}: $0.49 \frac{\text{mrem}}{\text{h}}$

H_{GRN}: $0.01 \frac{\text{mrem}}{\text{h}}$

H_{HEN}: $0.14 \frac{\text{mrem}}{\text{h}}$.

The total dose rate is 0.64 $\frac{\text{mrem}}{\text{h}}$. Although this slightly exceeds the design goal of 0.5 $\frac{\text{mrem}}{\text{h}}$, the design goal is based upon 8 hours of exposure and the linac is expected to operate for a much shorter length of time. In addition, the estimated contribution by the high energy radiations is highly conservative, at the relevant energies ($E \leq 200$ MeV).

4.5.1.2 Positron Converter:

The power loss at the positron converter is significantly higher than that in the first linac and therefore requires more than 2.0 m of concrete shielding. With 2.5 m of concrete shielding, the computed dose rates at 3.4 m are:

$$\dot{H}_{BREM}: \quad 0.60 \ \frac{\text{mrem}}{\text{h}}$$

$$\dot{H}_{GRN}: \quad 0.01 \ \frac{\text{mrem}}{\text{h}}$$

$$\dot{H}_{HE}: \quad 0.31 \ \frac{\text{mrem}}{\text{h}}$$

The total dose rate is 0.92 $\frac{\text{mrem}}{\text{h}}$. Although this exceeds the design goal for continuous operation, the linac is expected to operate for a much shorter duration and the estimated contribution from high energy radiations is still conservative. In the event of continuous linac operation, localized lead shielding (~5 cm) around the converter can easily be added.

4.5.1.3 Second Linac:

In the second linac, the power losses are down significantly due to lower positron current and the suggested 2.0 m concrete shielding is more than adequate. However, since it is also planned to use the system to accelerate only electrons, the power losses were computed for this case. Although the computed total dose rate would be 2.5 $\frac{\text{mrem}}{\text{h}}$, this was based on the assumption of the same high current in the first linac as needed for positron production. Assuming a much reduced electron current, as would be the case for e^- acceleration alone, would reduce the dose rate to well within the design goal. An additional mitigating factor in the linac loss computation is that all calculations assumed point losses which lead to higher dose estimates than if the losses are distributed along the length of the linac.

4.5.2 Shielding for the Booster Synchrotron

4.5.2.1 Shielding Requirements for Injection of Electrons from the Linac to the Booster Synchrotron

Using the maximum electron energy of 650 MeV at injection from the linac to the booster, dose rates were computed for the following parameters. The distance of closest approach is assumed to be 4 m and 1.5 m of concrete shielding exists at the point of injection. The number of electrons accelerated per second is taken as 1.15×10^{10} and an 80% loss rate is assumed at a point. With these assumptions, the dose rates are:

$$\dot{H}_{BREM}: \quad 0.44 \frac{\text{mrem}}{\text{h}}$$

$$\dot{H}_{GRN}: \quad 0.02 \frac{\text{mrem}}{\text{h}}$$

$$\dot{H}_{HEN}: \quad 0.75 \frac{\text{mrem}}{\text{h}}$$

The total dose rate is $1.21 \frac{\text{mrem}}{\text{h}}$. Assuming a 20% operational time for injection, which is reasonable, the total dose rate would become $0.24 \frac{\text{mrem}}{\text{h}}$, below the design goal of $0.5 \frac{\text{mrem}}{\text{h}}$. As an alternative, localized lead shielding (5 - 10 cm) at points of high loss in the injection system will also reduce radiation levels to below the design goal.

4.5.2.2 Shielding Requirements for Injection into the Main Ring from the Booster Synchrotron

Although there are several claims of low and high values for the injection efficiency, we assume, as in the case of injection to the booster from the linac, a point loss of 80% of the beam. The maximum energy is taken as 6.6 GeV. With these assumptions, the computed dose rates at 4 m with 1.5 m of concrete are:

$$H_{BREM}: \quad 4.5 \ \frac{\text{mrem}}{\text{h}}$$

$$H_{GRN}: \quad 0.2 \ \frac{\text{mrem}}{\text{h}}$$

$$H_{HEN}: \quad 7.6 \ \frac{\text{mrem}}{\text{h}}$$

The total dose rate is 12.3 $\frac{\text{mrem}}{\text{h}}$, which is above the design goal of 0.5 $\frac{\text{mrem}}{\text{h}}$. Now, adding 10 cm of lead (2 TVLS) would reduce the photon dose rate to 0.04 $\frac{\text{mrem}}{\text{h}}$, thus making it essentially negligible. Although there would be a reduction in the neutron dose rates also, we assume conservatively that 7.8 $\frac{\text{mrem}}{\text{h}}$ is due to the neutrons (giant resonance and high energy radiations). Assuming only a 20% operational time for injection, the dose rate would become 1.6 $\frac{\text{mrem}}{\text{h}}$, still three times higher than the design objective. An additional 50 cm of concrete or 20 cm of dense polyethylene at the high loss point(s) of the injection system will reduce the dose rates to below the design goal. This additional concrete or polyethylene, along with 10 cm of lead, is required only at the loss points of injection, such as septum magnets, bump magnets, or other bending and focusing magnets in the first quadrant following the injector.

4.5.2.3 Accidental Loss of Beam in Booster

For this case, consider a point loss of the electron beam (1.15 x $10^{10}e^{+}$ at 6.6 GeV) along the synchrotron ring. Assuming the distance of closest approach is 4 m and the shielding is 1.5 m of concrete, the dose per occurrence would be:

H_{BREM}: 1.58×10^{-3} mrem

H_{GRN}: 7.15×10^{-5} mrem

H_{HEN}: 2.80×10^{-3} mrem

For 1000 fills of the storage ring per year, with one occurrence for each 500 pulses in the synchrotron during filling, the number of occurrences would be about 4000 $\left(\frac{4.5 \times 10^{12}\ e^{+}\quad 1000\ \text{fills}}{1.15 \times 10^{10}\ e^{+}\ (0.2)\ 500}\right)$. This would result in a total dose of 17.7 mrem.

4.5.3. Storage Ring Shielding

The shielding calculations for the storage ring were based upon the assumption that the maximum beam of $4.5 \times 10^{12}\ e^{+}$ at 6.6 GeV must be shielded. Shielding tunnel dimensions of 9' x 9' were used, and a concrete thickness of 1.5 m on both sides and top of the tunnel on the experimental area side were assumed. A nominal circumference of 800 m for the ring was used in the calculations. In addition, an exclusion area of ~ 1 m from the tunnel was assumed so that the distance of closest approach was taken as 4 m. For the shielding on the inside of the ring, a concrete thickness of 0.5 m of concrete and, at least, 2 m of soil in the beam plane were assumed.

4.5.3.1 Continuous Loss During Beam Decay

As the electron beam moves around the storage ring, there will be a continuous loss of electrons from the beam due to several different factors. Collisions of electrons with gas molecules, interaction of beam particles, and orbital excursions all lead to electrons being lost from the beam and striking the vacuum chamber. Using an approximate calculation suggested by Swanson (SWA 85), the contributions from each radiation component to a point, due to uniform interactions around the ring circumference were calculated for both the unshielded case and with 1.5 m of concrete shielding. These are shown in Figs. 1-3. When these distributions are integrated over all angles, the result is the cumulative contribution at the point due to the loss of the entire beam. The integrated contributions, for the shielded case, are:

$$H_{BREM}: \quad 3.16 \times 10^{-4} \frac{\text{mrem}\cdot\text{deg}}{\text{J}}$$

$$H_{GRN}: \quad 7.91 \times 10^{-6} \frac{\text{mrem}\cdot\text{deg}}{\text{J}}$$

$$H_{HEN}: \quad 5.12 \times 10^{-4} \frac{\text{mrem}\cdot\text{deg}}{\text{J}}$$

Assuming 4.5×10^{12} e^+ at 6.6 GeV gives 4752J of stored energy. For a beam decay rate of 3h, the power loss is 4.4 J/h deg and the resultant dose rates are:

$$H_{BREM}: \quad 1.39 \times 10^{-3} \frac{\text{mrem}}{\text{h}}$$

$$H_{GRN}: \quad 3.48 \times 10^{-5} \frac{\text{mrem}}{\text{h}}$$

$$H_{HEN}: \quad 2.25 \times 10^{-3} \frac{\text{mrem}}{\text{h}}$$

The total dose rate is then $3.67 \times 10^{-3} \frac{\text{mrem}}{\text{h}}$, well within the guideline. Moreover, the beam lifetime at design objective is 8 - 10 h so the dose rate at design objective would be $1.38 \times 10^{-3} \frac{\text{mrem}}{\text{h}}$ or less. However, the simplifying assumption of uniform beam loss along the entire circumference of the ring generally does not prove out. Experience, at Aladdin and NSLS (SWA 85, BNL 51584), indicate localized loss patterns at open ends of bending magnets, around the straight sections, at maximum dispersion points in quadrupole magnets, and bremsstrahlung jets at the end of the straight sections. Therefore, additional localized shielding in the form of lead (10 cm) for the bremsstrahlung and dense polyethylene (15 cm) for the high energy neutron component may have to be provided at high loss points in the system.

At the present time, 1.5 m of concrete on the experimental area side is deemed more than adequate. On the inside of the ring, the combination of 50 cm of concrete, 2 m of soil, and the increased distance to the dose point offer the same equivalent shielding as the 1.5 m of concrete on the outside of the ring.

4.5.3.2. Loss of Total Beam at a Single Point

For the case of a total beam loss at a single point, two aspects need to be considered: the transverse component and the radial component. For the transverse component, the distance of closest approach is taken as 4 m. The loss of the entire beam at a point represents 4752 J of stored energy. Assuming 1.5 m of concrete as the transverse shielding, the resulting doses are:

$$H_{BREM} = 0.62 \text{ mrem}$$

$$H_{GRN} = 0.03 \text{ mrem}$$

$$H_{HEN} = 1.04 \text{ mrem}$$

This gives a total dose per occurrence of 1.69 mrem. Assuming such an event occurs even as frequently as once a month, the yearly dose would be 20.2 mrem or about 2% of the guideline value.

If the dose along the radial component is considered, the minimum distance to the dose point would be 25.9 m, of which 9.1 m would be concrete due to the slant penetration. This increase in shielding thickness would offset the increased bremsstrahlung in the forward direction and result in negligible doses.

4.5.3.3 Loss of Beam into an Optical Beam Line

In the event of a dipole failure, part of the electron beam could be lost down an optical beam line. This could result in very serious exposures and high radiation in the experimental area. For this reason, all beam lines need to be shielded with lead shutters, 25-cm thick in the beam direction and 10 cm transverse to the beam direction. The shutters should be located within the shield tunnel to adequately shield the neutrons produced by the photon shower in the lead.

On the assumption that 10% of the beam could be lost down a beam line, a resultant unshielded bremsstrahlung dose of 2.6×10^4 rem at 1 m, due to stopping the entire beam, would be produced in the forward direction. If this occurred near the inside of the shielding wall, the resultant bremsstrahlung dose on the outside of the shield at 1 m from the tunnel wall along the beam pipe would be reduced to about 0.04 mrem due to the lead shielding of the shutter and distance factor (~2.5 m). The scattered radiation dose coming through the tunnel wall would be negligible.

Since this accidental condition has a very low probability of occurrence, and it is unlikely that as much as 10% at the beam would be directed down a beam pipe, no additional shielding is recommended.

4.5.3.4 Loss of Forward Directed Beam into Concrete Shield

Considering a shielding design which resembles a ratchet wheel or "sawtooth" pattern, part of the lost beam may strike the shield head-on. As in the case of the accidental loss of beam down an optical beam line, assume

10% of the beam strikes the concrete shielding. The distance to the dose point will then be 2.5 m. The resulting doses per occurrence would then be:

$$H_{BREM}: \quad 3.1 \text{ rem}$$

$$H_{GRN}: \quad 7 \times 10^{-3} \text{ mrem}$$

$$H_{HEN}: \quad 0.27 \text{ mrem}$$

In this case, the bremsstrahlung component dominates and 10 cm of lead shielding in front of the concrete shielding, will reduce the bremsstrahlung contribution to 0.03 rem.

4.5.3.5 Scattered Radiation into a Beam Line

In addition to the lead shutters in the beam line, lead collars will need to be installed to insure that scattering of bremsstrahlung radiation is intercepted by 10 cm of lead shielding. This lead collar must extend along the beam tube to effectively block any optical path between the electron orbit and the beam tube aperture.

4.5.3.6 Dose Rate in Experimental Areas

The dose rate in the experimental areas was computed with the aid of Fig. 4 which shows the various dose contributions outside the ring at different distances, assuming uniform beam loss around the circumference. For the experimental areas, a nominal distance of 40 m was assumed and a beam lifetime of 3 h was used, giving a power loss rate of 4.4 J/h deg. Using dose components from the figure, the dose rates become:

$$\dot{H}_{BREM}: \quad 1.1 \times 10^{-4} \frac{\text{mrem}}{\text{h}}$$

$$\dot{H}_{GRN}: \quad 2.7 \times 10^{-6} \frac{\text{mrem}}{\text{h}}$$

$$\dot{H}_{HEN}: \quad 1.7 \times 10^{-4} \frac{\text{mrem}}{\text{h}}$$

The total dose rate is $2.8\ \frac{\mu\text{rem}}{\text{h}}$ which is well within the guidelines.

4.5.3.7 Dose to the Public

Using the information in Fig. 4, assuming a distance of 500 m to the site boundary, and total operation time of 3000 h per year, the total annual dose at the site boundary due to direct radiation was computed to be 18 μrem/yr.

The skyshine contribution due to the high energy component was computed using the expression for a well-shielded accelerator:

$\phi(r) \sim \frac{aQ\, e^{-\frac{r}{\lambda}}}{4\pi r^2}$, in which a and λ are constants, $\phi\ (r)$ is the flux density $\frac{n}{cm^2\ s}$, Q is the source strength in n/s, and r is the distance to the dose point in cm. Values for a and λ are from experimental data obtained at DESY (RIN75). The values used ($a = 7$, $\lambda = 3.3 \times 10^4$ cm) give the largest flux density values. Values of Q were computed based upon the yield ($0.12\ \frac{n}{e}$) given by Bathow (BAT 67) for 6.3 GeV:

$$Q = .12\,(\frac{n}{e})\frac{4.5 \times 10^{12} e}{1.08 \times 10^4 s}\ e^{-3.07} = 2.3 \times 10^6\ \frac{n}{s}\ ,$$

for an assumed three hour beam lifetime.

For an assumed distance of 500 m,

$$(50{,}000) \sim \frac{7(2.3 \times 10^6)e^{-\frac{5 \times 10^4}{3.3 \times 10^4}}}{4\pi(5 \times 10^4)^2} = 1.13 \times 10^{-4}\ \frac{n}{cm^2\ s}.$$

Using the conversion factor $1 \frac{\text{mrem}}{\text{h}} = 3 \frac{\text{n}}{\text{cm}^2 \cdot \text{s}}$, as suggested by FASSO (FAS 84), the dose rate becomes

$$\dot{H} = \frac{1.13 \times 10^{-4} \frac{\text{n}}{\text{cm}^2 \cdot \text{s}}}{3 \frac{\frac{\text{n}}{\text{cm}^2 \cdot \text{s}}}{\text{mrem/h}}} = 3.8 \times 10^{-5} \frac{\text{mrem}}{\text{h}}, \text{ and}$$

for an assumed 3000 h of operation per year, the annual dose would be 0.11 mrem. If the photon dose due to skyshine is in the same ratio to the high energy component as for the case of direct radiation, then the annual skyshine photon dose would be 0.07 mrem.

The total annual dose from both direct and skyshine radiation is about 0.2 mrem/yr which is within the guidelines.

REFERENCES

DOE 81 U.S. Department of Energy requirements for radiation protection, DOE order 5480.1 Chg.6, Chap. XI-3 (1981).

DOE 84 U.S. Department of Energy, Proposed Revision of DOE Order 5480.1A, "Radiation Standards for Protection of Public," memorandum dated Sept. 17, 1984. REF. P.E.-243 (1984).

FAS 84 A. Fasso, K. Goebel, M. Hoefert, G. Rau, H. Schonbacher, G. R. Stevenson, A. H. Sullivan, W. P. Swanson, and J.W.N. Tuyn, "Radiation Problems in the Design of the Large Electron-Positron Collider (LEP)," CERN 84-02, (5 March 1984).

BAT 67 G. Bathow, E. Freytag, and K. Tesch, "Measurements on 6.3 GeV Electromagnetic Cascades and Cascade Produced Neutrons," NUC. PHYS., B2(1967), 669-689.

ALS 73 R.G. Alsmiller, Jr. and J. Barish, "Shielding Against the Neutrons Produced when 400-MeV Electrons are Incident on a Thick Copper Target," Particle Accelerators, 5, (1973), 155-159.

TES 79 K. Tesch, "Data for Simple Estimates of Shielding Against Neutrons at Electron Accelerators," Particle Accelerators, 9, (1979), 201-206.

DIN 77 H. Dinter and K. Tesch, Dose and Shielding Parameters of Electron-Photon Stray Radiation from a High Energy Electron Beam," Nuc. Inst.. Meth., 143, (1977), 349-355.

NEL 68 W. R. Nelson, "The Shielding of Muons Around High Energy Electron Accelerators: Theory and Measurement," Nuc. Inst. Meth., 66, (1968), 293-303.

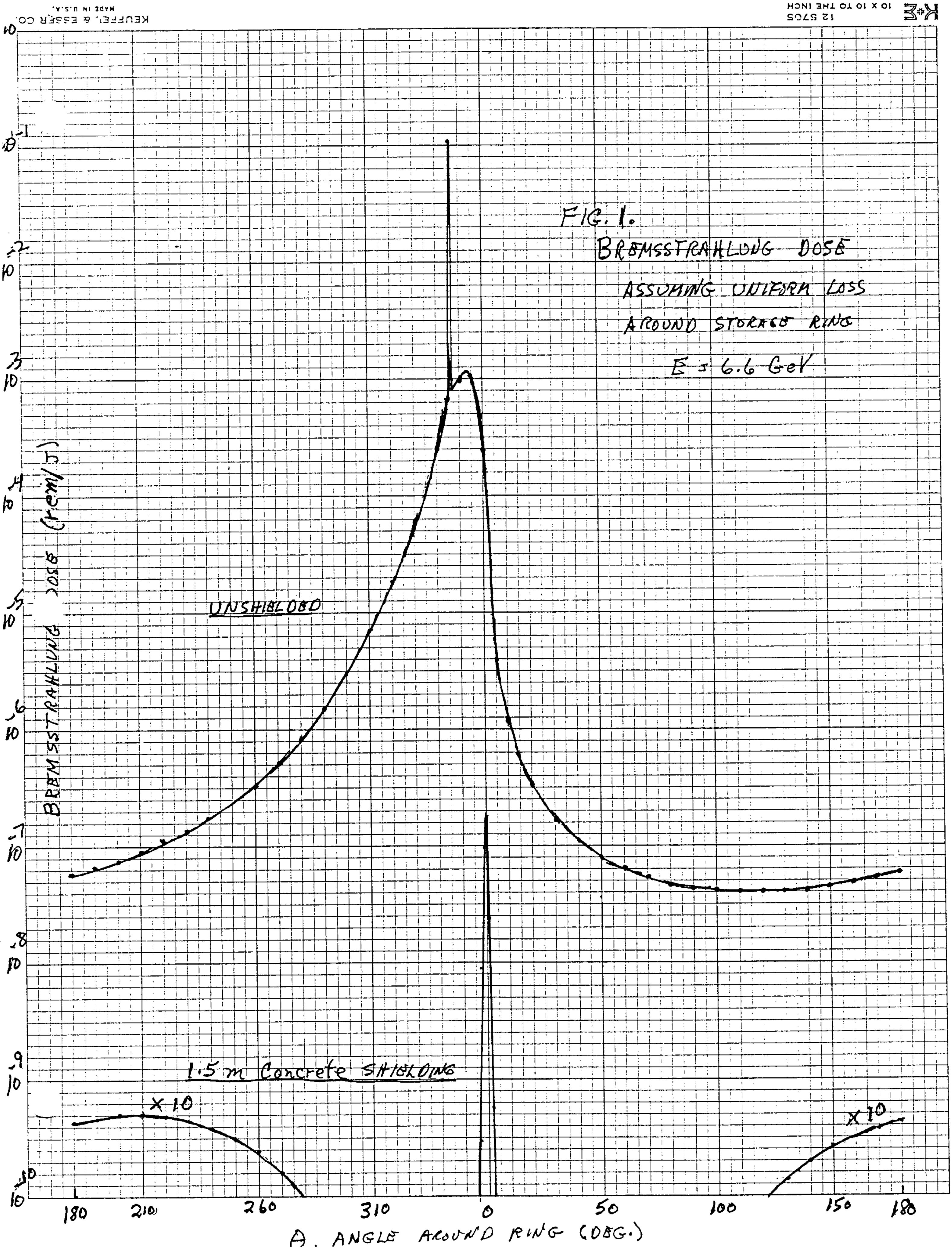
BAT 70 G. Bathow, E. Freytag, M. Kobbeling, K. Tesch, and R. Kajikawa, "Measurement of Longitudinal and Lateral Development of Electromagnetic Cascades in Lead, Copper, and Aluminum at 6.0 GeV," Nuc. Phys., B20, (1970), 592-602.

RIN 75 A. Rindi and R. H. Thomas, "Skyshine - A Paper Tiger?," Particle Accelerators, Vol. 7 (1975), 23-39.

SWA 79 W. P. Swanson, Radiological Safety Aspects of the Operation of Electron Linear Accelerators," Technical Report Series No. 188, IAEA, Vienna, 1979, and references therein.

SWA 85 W. P. Swanson, P. M. DeLuca, R. A. Otte, and S. W. Schilthelm, "Aladdin Upgrade Design Study: Shielding," University of Wisconsin, 1985.

BNL 51584 K. Batchelor, Editor, National Synchrotron Light Source Safety Analysis Report, Brookhaven National Laboratory, July 1982.



KEUFFEL & ESSER CO. MADE IN U.S.A.
K+E 10 X 10 TO THE INCH 12 5705
FIG. 1.
BREMSSTRAHLUNG DOSE
ASSUMING UNIFORM LOSS
AROUND STORAGE RING
E = 6.6 GeV
UNSHIELDED
1.5 m Concrete SHIELDING
X 10
X 10
BREMSSTRAHLUNG DOSE (rem/J)
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
180
210
260
310
0
50
100
150
180
A. ANGLE AROUND RING (DEG.)

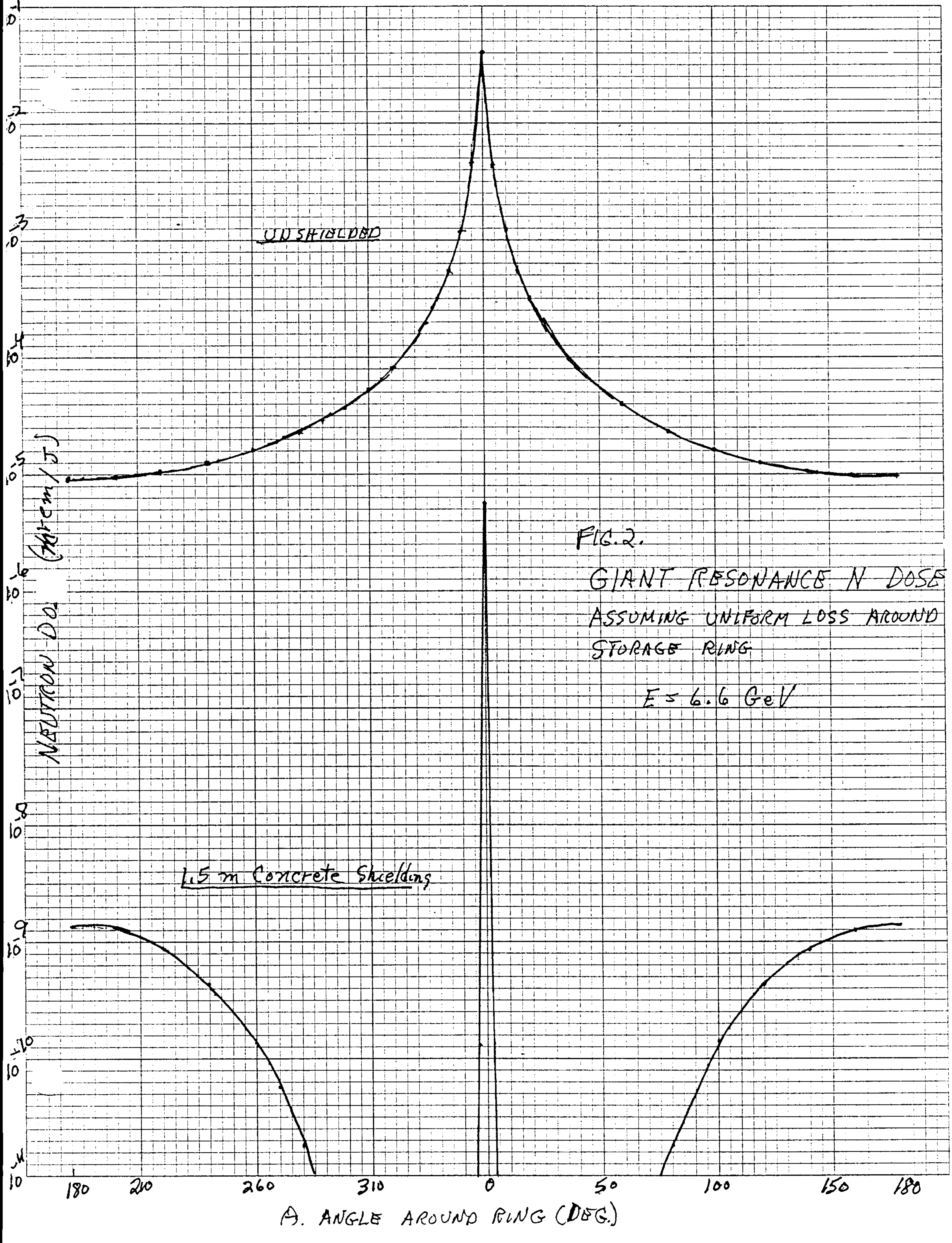
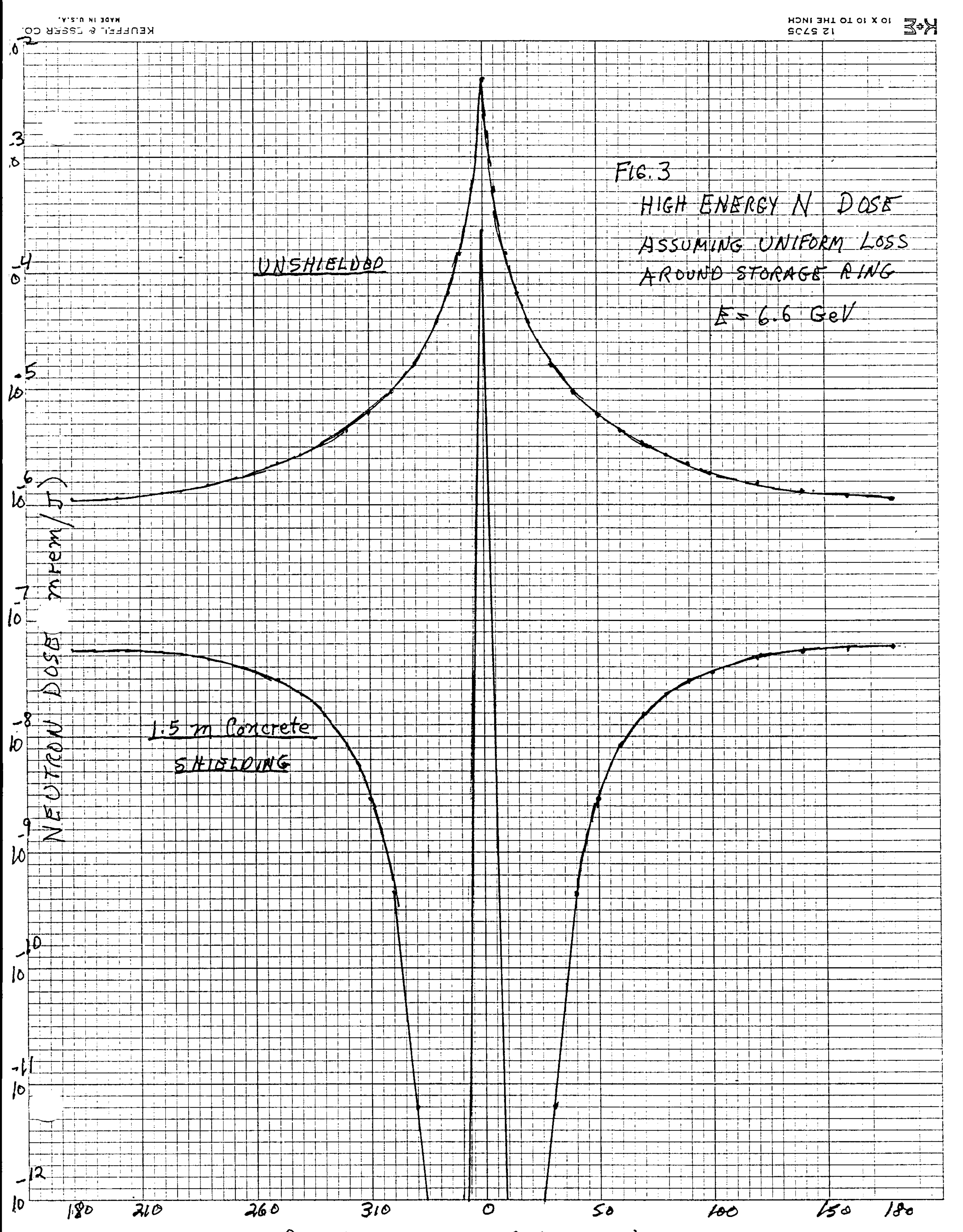


FIG. 2.
GIANT RESONANCE N DOSE
ASSUMING UNIFORM LOSS AROUND
STORAGE RING

$E = 6.6$ GeV



KEUFFEL & ESSER CO.
MADE IN U.S.A.
K+E 10 X 10 TO THE INCH
12 5705
FIG. 3
HIGH ENERGY N DOSE
ASSUMING UNIFORM LOSS
AROUND STORAGE RING
E = 6.6 GeV
UNSHIELDED
1.5 m Concrete
SHIELDING
NEUTRON DOSE (mrem/J)
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
180
210
260
310
0
50
100
150
180
θ, ANGLE AROUND RING (DEG.)

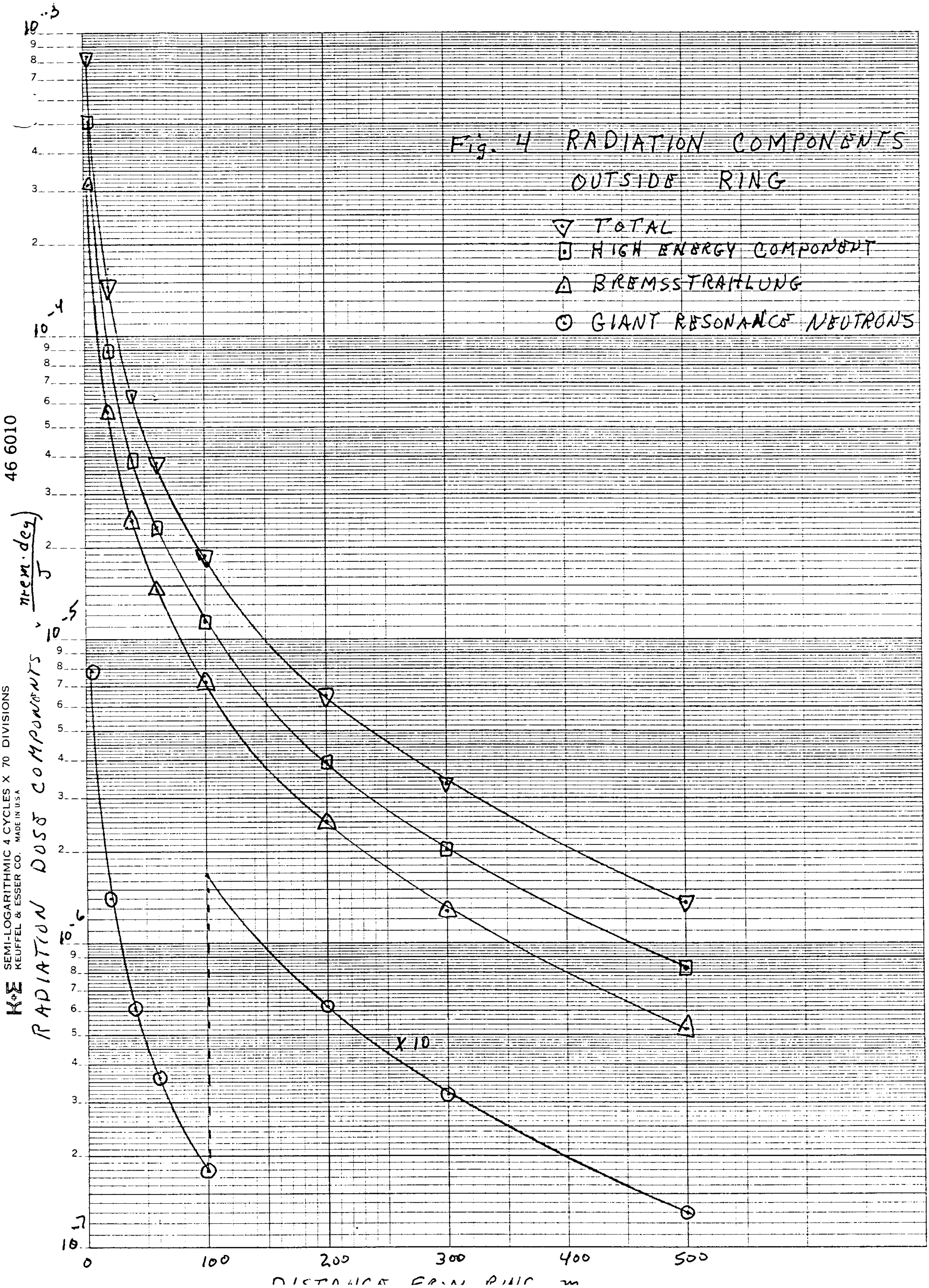


Fig. 4 RADIATION COMPONENTS OUTSIDE RING
TOTAL
HIGH ENERGY COMPONENT
BREMSSTRAHLUNG
GIANT RESONANCE NEUTRONS
X 10
RADIATION DOSE COMPONENTS, mrem·deg / J
DISTANCE FROM RING m
0
100
200
300
400
500
46 6010
SEMI-LOGARITHMIC 4 CYCLES X 70 DIVISIONS
KEUFFEL & ESSER CO. MADE IN U.S.A.